Risk communication for critical civil infrastructure systems

Jack Baker[1], Jason Coray[2], Paul DeStefano[3], Leonardo Dueñas-Osorio[4], Stephanie King[5] and Lance Manuel[6]

[1] Stanford University, Stanford, CA, *bakerjw@stanford.edu*
[2] Marx|Okubo Associates, Inc., San Francisco, CA, *jason_coray@marxokubo.com*
[3] The Louis Berger Group, East Orange, NJ, *pdestefano@louisberger.com*
[4] Rice University, Houston, TX, *leonardo.duenas-osorio@rice.edu*
[5] Weidlinger Associates, Inc., Mountain View, CA, *sking@wai.com*
[6] University of Texas, Austin, TX, *lmanuel@mail.utexas.edu*

ABSTRACT

The objective of this paper is to review and evaluate current methods for communicating risk within the context of infrastructure management decision support systems. A generic model of a risk-based infrastructure management system is presented to illustrate important relationships of key decision support functions and the critical flow of risk communication within this framework. The model includes three primary functions that are deemed necessary to effectively manage risk, namely (i) risk assessment, (ii) decision analysis, and (iii) executive decision/policy making, which typically involve engineers, statisticians, decision analysts, and owner/stakeholders. Another important function of risk-based management systems discussed in the paper includes the communication of risk to system users. The paper will present key metrics and performance measures used to communicate risk by and among various agencies and owners of critical infrastructure systems. The study concludes with a general assessment of the current means and methods of communicating risk within the framework of risk-based civil infrastructure management systems and identifies important needs for future research related to developing more effective and efficient communications.

INTRODUCTION

A key principle developed by ASCE's Critical Infrastructure Guidance Task Committee in 2009 was to quantify, *communicate*, and manage risk. Critical infrastructure systems are facilities and assets – such as roads and bridges, water supply, wastewater treatment, flood-reduction structures, telecommunications, and power grids – so vital that their destruction or incapacitation would disrupt the security, economy, safety, health, or welfare of the public (ASCE, 2009). Effective communication of the hazards and inherent risks to our civil infrastructure facilities between analysts, decision-makers, stakeholders/owners, and users is essential to the nation's prosperity and well-being. The purpose of this paper is to address the scope, metrics, application domains, issues and challenges, and current research needs of such risk communication.

Recent catastrophes such as the 2010 San Bruno, California pipeline explosion, hurricane Katrina in 2005, and Japan's 2011 Tohoku Earthquake and subsequent tsunami and nuclear crisis highlight the need for effective risk communication. When the public feels misled or uninformed about risks from pipeline, levee failures, radiation exposure, etc., effective recovery becomes much more difficult. Adequate communication of risk metrics includes the conveyance of accurate information regarding the underlying hazards, risk assessment and performance criteria related to civil infrastructure assets. Further complicating such an effort is the combination of risks and increasing interdependence of infrastructure systems. The coupling between infrastructures systems, which occurs at the physical level where systems consume or produce commodities for other systems, and also at the institutional level to efficiently coordinate operations across systems, demands a great deal of communication to ensure adequate service during both normal operation and after major disruptions (Duenas-Osorio et al. 2007, Adachi and Ellingwood 2008, Zhang and Peeta 2010). Successful and efficient risk communication is necessary for the proper functioning of government and industry insofar as regulatory, legislative, and policy decisions are concerned and as they relate to, and occur in an environment of scarce resources, legal liability, and media attention, all within the court of public opinion.

The Technical Council on Life-Cycle Performance, Safety, Reliability and Risk of Structural Systems was founded to set new directions in the field of structural safety and reliability within SEI/ASCE. Within that Technical Council, Task Group 3: Risk Assessment of Structural Infrastructure Facilities and Risk-Based Decision Making, was formed to promote the study, research and applications of scientific principles of risk assessment and risk-based decision making in structural and infrastructure engineering. This paper is a product of that task group, and focuses on effective communication within the context of risk-based, civil infrastructure management systems.

In general, communication within risk-based management systems occurs (i) between the risk assessor and decision analysts, (ii) between decision analysts and owners/stakeholders, and (iii) between owners/stakeholders and those impacted by the decision (users). Communication between system users and owners or risk assessors varies and depends on the infrastructure system being evaluated. Risk assessors typically gather and evaluate data relating to failure modes and effects and probabilities of failure. The decision analyst will utilize the inputs provided by risk assessors and develop a model for evaluating optimal strategies based on the goals and objectives of the owner/stakeholders who also pursue user-oriented goals. This paper will present basic needs and requirements of these communication links and how they differ, but will focus primarily on the links between risk assessor-decision analysts-owners, where engineering expertise and principles are more applicable. Although risk management systems are typically developed for a specific application and purpose, a generic framework is illustrated in Figure 1 to identify important communication needs of these systems.

Although stakeholders and users of civil infrastructure systems are shown as separate entities in Figure 1, this is not always the case. The figure also illustrates that, since risk assessors and decision analysts ultimately provide facility owners with a basis to eventually make their case to stakeholders and users, effective communication between all four entities is critical to an efficient risk management process. The ASCE Critical Infrastructure Guidance Task Committee has acknowledged that for most critical infrastructure projects, risk has not been properly communicated to the end-users (typically, public) and other entities, and a major shift in communication is needed to properly develop projects and programs for critical infrastructure (ASCE 2009).

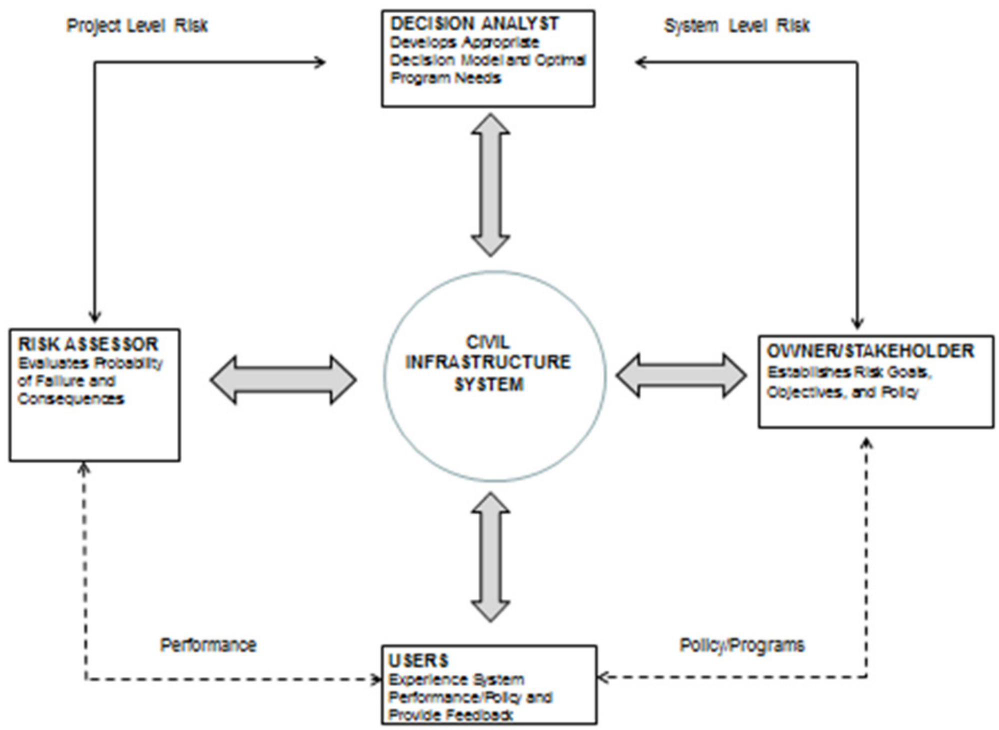

Figure 1: Risk-Based Civil Infrastructure Management and Communication Framework

RISK COMMUNICATION BETWEEN ENTITIES

While risk can in theory be universally quantified as event probabilities multiplied by their consequences and summed over all possible events, in practice a variety of related metrics are used to evaluate and communicate risk. The use of alternative metrics, and their variation across domains and audiences, is in part due to the independent development of risk assessment approaches within and across fields, which affect what type of metric is most effective for communication of estimated risks. Further, the various stages of the risk management framework illustrated in Figure 1 may require varying approaches to address issues important to each specific stage. To illustrate, we briefly discuss metrics and issues associated with risk communication across risk management stages and application domains.

Linking risk assessment and decision analysis

Much communication at this stage serves the purpose of ensuring compliance with regulatory documents requiring minimum safety standards. For these purposes, many documents establish a specific type of event occurrence, and require the analyst to ensure only that the annual probability or rate of that event's occurrence falls below an acceptable level (without any need to quantify the consequences of the event). For example, DOE-1020 specifies annual probabilities of seismic failure for nuclear facilities to be between 10^{-3} and 10^{-5}, depending on the Performance Category of the component or facility being considered (Kennedy and Short 1994). For buildings, ASCE 7-10 specifies that code-designed buildings will have less than a 1 percent probability of collapse due to earthquake shaking within a 50 year period (ASCE 2010). FEMA produces maps of locations with annual flooding probabilities of 0.01 and 0.002 ("100 year" and "500 year floods") for the purposes of both communicating flood risk and requiring flood insurance (FEMA 2012).

Conversely, in other cases the probability of the event is fixed and only the consequences of the event (in terms of system performance) are analyzed. For example, ASCE 43-05 (2005, Section 1.3) specifies that nuclear facilities should achieve a 1% probability of unacceptable performance in a Safe Shutdown Earthquake ground motion, and a 10% probability of unacceptable performance for a ground motion equal to 150% of a Design Basis Earthquake ground motion. In all of the above cases that simplify the complete risk calculations, the simplification has been done because the approximate metric is easier to obtain and evaluate, and is presumably also nearly as informative as a more complete risk metric.

Bridge network-level performance is typically measured by the percent of bridges structurally deficient or functionally obsolete and overall system condition related measures developed at both the state and national level. Although one can interpret a certain level of risk from the various condition related measures currently available in the database systems, specific risk metrics have not been quantified, standardized, nor typically utilized in bridge and transportation system decision and policy making processes. When dealing with multiple utility systems serving the same region, there is an emerging trend to indirectly communicate risk and resilience via targets for recovery time, which facilitate taking into account several factors that affect restoration, including physical interdependencies across systems, institutional dependencies, availability of resources, and other regulatory and local constraints (SPUR 2009).

Yet another way to quantify engineered systems functionality and associated risks for decision analyses is to monitor historical performance and rely on best practices to not deviate from expected trends, as in the case of the power distribution sector with its sustained interruption indices, such as the System Average Interruption Duration Index (SAIDI) or the most recent Customers Experiencing Long Interruption Durations (CELID) metric (IEEE 2012). Alternatively, some water distribution utilities communicate their risks via trade-off analyses that build upon multi-objective optimization and show several solutions that balance cost and capacity (i.e., risk reduction) without having to determine a single "best" solution during the risk assessment and analysis process. This approach enhances flexibility in subsequent decision-making by informing decision analysts of reasonable alternatives that address in different ways relevant performance attributes such as system pressure or water quality (HAESTAD 2003).

Clearly, the metrics to be used at this stage of decision analysis depend upon the stakeholders in the system. Public stakeholders such as government agencies often need quantified risk assessment results using a transparent publicly-available methodology or process. They have to be able to defend their decisions (sometimes in a court of law) and the assessment results (and all data) can sometimes become public record. Private stakeholders can be vaguer about how they reach their risk management decisions, especially if they are not a publicly-traded company, and if their decision does not violate any regulatory requirements regarding safety.

Linking decision analysis to owners and stakeholders

Risk communication is used to inform owners and stakeholders and manage expectations. Clear communication is important to build trust, so an owner has the confidence necessary to communicate their decisions to the public or facility users.

In some cases of risk assessment and decision analysis, safety metrics have been developed with the objective of being able to communicate the decision to the public, as evident with lifeline systems when providing expected times to service recovery. In other cases, they have been developed because they are feasible to compute in the analysis stage, even if they are not the metrics that stakeholders will evaluate. ASCE 7-10's 1% probability of collapse in 50 years metric can be communicated to owners and compared to other risks, but is never explicitly computed for a specific building design. The design stage for a specific building will check that member force and displacement levels are tolerable at a "Maximum Considered Earthquake" level, where that level is carefully calibrated such that passing the design stage check implies that the overall risk target will be met (Luco et al., 2009). Similarly, IEC 61400-1 specifies that the service life of wind turbines shall be at least 20 years, and that is a metric understandable to a broad range of stakeholders. But the metric at the design checks stage evaluates performance under reference wind in excess of the 50-year wind speed at the turbine site (IEC, 2005). The use of a 50-year period for the above earthquake and wind checks is also notable here as a communication issue; while 50-year-probabilities could be expressed as equivalent annual probabilities, the 50-year probabilities are often more easily interpretable by owners and other stakeholders who can directly see the probability of disruption over a typical lifetime of an asset.

One other effective way in which metrics are sometimes communicated to stakeholders is to report probabilities or losses for a scenario event. This may be easier to communicate than an annual probability of failure or a risk measure that combines probabilities with consequences, and audiences often find losses easier to understand if they are tied to some well-quantified scenario. Scenario-based communication of risk is particularly easy for failures due to triggering events such as natural disasters, but not effective for failures due to fatigue, corrosion or other normal events. Terrorism risk assessment in particular is typically a "conditional" risk assessment given occurrence of a scenario event, since the estimated probability of the event is dynamic and not always known (or is restricted information).

Linking owners and stakeholders to users

In communicating risk to the non-technical users and the general public, the use of qualitative terms such as "likely" "probably", etc. are sometimes used in place of numerical metrics, unlike at the risk assessment and decision analysis stage where numerical metrics are common. For example, the U.S. Army Corps of Engineers (USACE) classifies dams' safety in terms of High, Medium, and Low risk to the general population. Another example is the use of signs on bridges that are posted for less than legal load limits or classified as "structurally deficient" or "closed." There have been attempts to link those subjective words with numerical probabilities (e.g., Vick, 2002), but users of subjective words do not often use such formal links.

Another area where communication at various stages of risk management differs is in the assessment of distributed or interacting systems. For example, highway bridges are typically designed and analyzed individually, without explicitly considering the impact of their loss of use on risk to a larger highway network. But users are presumably more concerned with the functionality of the overall system than with any individual bridge. In one of the few examples in practice, the *Seismic Retrofitting Manual for Highway Strictures* (Buckle et al. 2006) considers at least two methods for ranking bridges in a highway network, based on qualitative indices and estimates of losses, and advocates for the importance of bridges to the entire system, but without putting forward an implementable methodology—a task that is just starting to be addressed (Rokneddin et al. 2011).

Other efforts to build upon the notion of criticality assessment to communicate risk to users include the screening and evaluation phases from the American Lifelines Alliance (ALA 2005), as well as emerging approaches to rank the components within large-scale networked systems. The large size of infrastructure systems requires novel computational approaches that account for topological and non-network information as encoded in the spectral properties of the matrices that described the networks, which ultimately yield user-friendly rankings and correlations among system component criticalities.

Non-safety-related considerations

Much of the above discussion is focused on safety, as safety requirements are often defined in recommended practices or regulatory documents where provision of public safety is a primary objective. Metrics associated with consequences besides those related to safety are of growing interest, but often not explicit in design, operation or retrofit guidelines. This is a result of the difficulty in recommending actions or procedures to manage risk that must also compete with tradeoffs or limitations related to cost, infrastructure functionality, etc. If users are impacted by risk management decisions, and provision of safety is impacted by these other constraints or vice versa, communication of those constraints and safety goals may be an important component of risk communication. A few additional relevant issues and examples are discussed next.

For infrastructure systems, provision of service after an event is of primary interest, as some utility sectors allow setting system-level performance goals under exceptional conditions separate from normal operation goals to prevent overshadowing of trends if major event conditions are combined. For instance, owners of power generation and distribution infrastructure may communicate the risks associated with their service interruption in terms of percent blackout or brown out areas and periods, or in terms of more specialized metrics such as SAIDI, Energy not Supplied (ENS) or Loss of Load Probability (LOLP), which are benchmarked relative to normal data and to major event days or other contingency data (IEEE 2012). Resilience metrics constitute another emerging approach aimed at quantifying notions beyond safety by addressing resistant, absorptive, and restorative capabilities of engineered systems, thus merging technical and logistical concepts (Bruneau et al. 2003, SPUR, 2009, Ouyang and Dueñas-Osorio 2012). A variety of other metrics related to system-level performance, quantifying concepts such as robustness and vulnerability, are also continuing to evolve (e.g., Frangopol and Curley, 1987, Lind 1995, Baker et al., 2008).

Some civil engineering risk assessment procedures also explicitly evaluate business interruption and financial losses along with safety, reporting the consequences from each type of consequence separately (e.g., ATC, 2012). Non-safety- and safety-related risk metrics can be jointly considered using multi-attribute utility theory and multi-criteria decision analysis in alignment with previously discussed flows of risk information and their communication (Keeney and Raiffa, 1993). Another approach for simultaneously considering and communicating safety and non-safety-related risk metrics and constraints is to convert all metrics to equivalent dollar amounts. The Life Quality Index is such one approach for determining the equivalent dollar value of marginal increases in the safety of a system (Pandey et al., 2006, Ditlevsen and Friis-Hansen, 2009). While some industries and countries find this approach effective, it may raise objections from stakeholders who are unaware of or uncomfortable with the implicit tradeoffs that must be made between safety and other objectives.

A more general class of risk-related analysis to support risk communication and decision making is Life Cycle Assessment (LCA), which aims to assess the environmental, economic, and social costs of an infrastructure project over all stages of its lifespan (construction, operation and disposal). LCA and risk assessment may converge in the future for cases where non-safety-related impacts are also driving decision making. Assessing life cycle impacts and their effective communication in relation to civil infrastructure risk is an area of active and ongoing research (e.g., Chang and Shinozuka 1996, Biondini and Frangopol 2008).

Related to LCA concepts, the temporal distribution of risk consequences is another non-safety related issue that plays a role in risk metrics and their communication. Discounting future risk is generally understood to be important in ensuring that resources are appropriately used to minimize risk in the present and the future (Pate-Cornell 1984). Most researchers agree that the present value of future risk is the appropriate metric to use in order to reach rational decisions regarding risk mitigation. The choice of a discount rate can affect decision making, so communicating the assumed discount rate (and communicating the validity of discounting) to stakeholders is important in such cases.

CONCLUSIONS

This paper has presented a discussion of how risk is communicated between various parties as part of civil infrastructure risk management activities. It was seen that methods and metrics for communicating risk vary significantly depending upon the parties and the type of infrastructure under consideration.

Viewing the variety of metrics and approaches, the question arises as to whether consistency of metrics is desirable and feasible over widely varying industries and stakeholders. On one hand consistency of procedures would enable sharing of best practices across a wider array of situations, and the public would benefit from having a more clear understanding of his/her own risk and safety associated with operation of various infrastructure systems. Consistent risk metrics across different infrastructure assets is also important to planners, municipalities, etc. who must decide on priorities among competing issues (e.g., maintenance of bridges, pavements, rail, waterways). On the other hand, there are a number of situations and terms that are very industry-specific (e.g., core damage frequency for a single nuclear power plant, average service interruption for electrical networks); these metrics are very useful for specific applications, and should not be lost simply for the ideal of standardization. In the end, future progress likely entails retaining industry standard risk communication approaches, while also using collaboration through ASCE to facilitate sharing of best practices and standardization among the parties involved in managing infrastructure risk.

Moving forward, it is clear that more work is needed to assess and communicate risk for interacting and interdependent infrastructure systems. Some progress in this area has been noted above, but work is still underway on how to quantify risk in these complex systems, and to adopt and implement the needed procedures. Progress in this area should lead to more informed and efficient management of our increasingly complex and interconnected infrastructure systems.

While assessment of risk receives more attention, the above discussion aims to make clear that the communication is also an important aspect in research and implementation of risk management. Effective communication of risk between the various parties involved in management of civil infrastructure systems has a number of benefits. It builds credibility between parties, translates risk analysis results into useful formats, reduces uncertainty, and facilitates decision-making regarding allocation of resources among competing needs. For these reasons, effective risk communication has been noted as an important principle in a number of ASCE documents. We anticipate future progress on this topic, given its importance in management of critical infrastructure.

REFERENCES

Adachi, T., and Ellingwood, B. R., (2008). "Serviceability of earthquake-damaged water systems: effects of electrical power availability and power backup systems on system vulnerability". *Reliability Engineering and System Safety*, 93, 78–88.

ALA (2005). Guideline for assessing the performance of electric power systems in natural hazard and human threat events.

ATC (2012). *ATC-58, Guidelines for Seismic Performance Assessment of Buildings, 100% Draft*. Applied Technology Council, Redwood City, California.

ASCE (2005). *Seismic design criteria for structures, systems, and components in nuclear facilities*. ASCE Standard 43-05, Structural Engineering Institute, Working Group for Seismic Design Criteria for Nuclear Facilities, Reston, VA.

ASCE (2009). "Guiding principles for the nation's critical infrastructure." ASCE Critical Infrastructure Guidance Task Committee.

ASCE (2010). *Minimum Design Loads for Buildings and Other Structures,* ASCE Standard 7-10. American Society of Civil Engineers/Structural Engineering Institute, Reston, VA.

Baker, J. W., Schubert, M., and Faber, M. (2008). "On the assessment of robustness." *Structural Safety*, 30(3), 253–267.

Biondini, F., and Frangopol, D. M. (2008). *Life-Cycle Civil Engineering: Proceedings of the First International Symposium on Life-Cycle Civil Engineering, Varenna, Lake Como, Italy, June 10-14, 2008*. CRC Press.

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A., and Von Winterfeldt, D. (2003). "A framework to quantitatively assess and enhance the seismic resilience of communities." *Earthquake Spectra*, 19(4), 733-752.

Buckle, I., et al., (2006). *Seismic retrofitting manual for highway structures: part 1-bridges*. Springfield, VA: Federal Highway Administration, Office of Research, Development and Technology, Turner-Fairbank Highway Research Center.

Chang, S. E., and Shinozuka, M. (1996). "Life-Cycle Cost Analysis with Natural Hazard Risk." *Journal of Infrastructure Systems*, 2(3), 118-126.

Ditlevsen, O., and Friis-Hansen, P. (2009). “Cost and benefit including value of life, health and environmental damage measured in time units.” *Structural Safety*, 31(2), 136-142.

Dueñas-Osorio, L., J. I. Craig, and B. J. Goodno, (2007). “Seismic response of critical interdependent networks.” *Earthquake Engineering and Structural Dynamics*, 36(2): 285-306.

Ellingwood, B. R., Frangopol, D. M. (2010). “Life-Cycle Performance, Safety, Reliability and Risk of Structural Systems – A Framework for New Challenges.” *STRUCTURE*, NCSEA/CASE/SEI

FEMA (2012). National Flood Insurance Program Hazard Mapping Annex. Federal Emergency Management Agency. http://www.floodmaps.fema.gov/.

Frangopol, D. M., and Curley, J. P. (1987). “Effects of damage and redundancy on structural reliability.” *ASCE Journal of Structural Engineering*, 113(7), 1533–1549.

Frangopol, D. M., and Ellingwood, B. R. (2010). “Life-cycle performance, safety, reliability and risk of structural systems.” *Structure Magazine*, 7.

HAESTAD (2003). Advanced water distribution modeling and management. Waterbury, CT: Haestad Press.

IEC (2005), “Wind Turbines - Part 1: Design Requirements,” International Electrotechnical Commission IEC 61400-1 Ed.3.0.

IEEE (2012). IEEE Guide for electric power distribution reliability indices. IEEE Standard 1366-2012. New York: IEEE Power and Energy Society.

Keeney, R. and Raiffa, H. (1993) Decisions with Multiple Objectives: Preferences and Value Tradeoffs. Cambridge University Press. 592p.

Kennedy, R., and Short, S. (1994). *Basis for seismic provisions of DOE-STD-1020. UCRL-CR-111478 and BNL-52418*. Lawrence Livermore National Laboratory and Brookhaven National Laboratory.

Lind, N. C. (1995). “A measure of vulnerability and damage tolerance.” *Reliability Engineering & System Safety*, 48(1), 1–6.

Luco, N., Ellingwood, B. R., Hamburger, R. O., Hooper, J. D., Kimball, J. K., and Kircher, C. A. (2007). “Risk-targeted versus current seismic design maps for the conterminous United States.” *Proceedings of the 2007 Structural Engineers Association of California (SEAOC) Convention*.

Miles, S. B., (2011). “Participatory model assessment of earthquake-induced landslide hazard models.” *Natural Hazards*, 56: 749-766.

Ouyang, M., and L. Dueñas-Osorio, (2012). “Time-dependent resilience assessment and improvement of urban infrastructure systems.” *Chaos*, 22(3), 033122, 11p.

Pandey, M., Nathwani, J., and Lind, N. (2006). “The derivation and calibration of the life-quality index (LQI) from economic principles.” *Structural Safety*, 28(4), 341-360.

Pate-Cornell, M. E. (1984). “Discounting in risk analysis: capital vs. human safety: structural technology and risk.” *Proc. Symp. Structural Technology and Risk*, University of Waterloo Press, Waterloo.

Rokneddin, K., J. Ghosh, L. Dueñas-Osorio, and J. E. Padgett (2011). “Bridge retrofit prioritisation for ageing transportation networks subject to seismic hazards.”

Structure and Infrastructure Engineering, DOI: 10.1080/15732479.2011.654230

SPUR (2009). The resilient city: Defining what San Francisco needs from its seismic mitigation policies. San Francisco: SPUR.

Vick, S.G. (2002). "Degrees of Belief: Subjective Probability and Engineering Judgment," ASCE Press, Reston, VA.

Zhang, P., and Peeta S., (2011). "A generalized modeling framework to analyze interdependencies among infrastructure systems." *Transportation Research Part B: Methodological* 45(3), 553–579.